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Neutron Star Evolution with Internal Energy Dissipation by Vortex Creep

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ABSTRACT

The effect of internal energy dissipation on the thermal evolution of neutron stars has been examined. We adopt the heat generation formula as given by the superfluid vortex creep motion in the inner crust of the neutron star. We found that the internal heating largely slows down the cooling of the photon dominant era and hence yields considerably larger surface photon luminosity compared with the no heating case. Our calculations predict that even old neutron stars with the age of more than ~ 10^6 y still emit observable thermal radiations. These results completely change the conventional picture of the steep cooling and very low surface temperature for the old neutron stars. It was also found that if the pinning of the superfluid vortices to the lattice nuclei in the inner crust is strong, the internal heating influences also the neutrino cooling era and raises the surface photon luminosity significantly. We set the constraints on the physical parameters in the pinning region using the upper limits on the surface temperature of the nearby pulsars obtained by the Einstein observatory.

Subject headings:

I. INTRODUCTION

The neutron star is a fascinating object which is now widely accepted to be an important constituent in pulsars and compact galactic X-ray sources. The dynamical property of the neutron star has been studied through the pulse frequency variations of rotation-and accretion-powered pulsars. Shortly after the discovery of glitch (sudden pulse period jump) in Vela pulsar (Radhakrishnan and Manchester 1969; Reichley and Downs 1969), Baym et al. (1969) suggested the presence of the neutron superfluid and interpreted the post-glitch behavior in terms of the coupling of the superfluid core to the crust. This simple two-component model gave a good qualitative fit to the observational data of the glitch. Recently, however, the timing noise analysis of Crab pulsar (Boynton 1981) and Vela X-1 (Boynton et al. 1984) found that the neutron star is responding to rotational disturbances like a rigid body and ruled out the simple two-component model as an adequate description of the full dynamical behavior of the neutron stars.

One promising model for the pulsar glitch now is the sudden unpinning of the superfluid vortices in an inner crust where they are normally pinned to the crustal nuclei (Anderson and Itoh 1975; Pines et al. 1980). Recently, Alpar et al. (1984a) developed a general theory for the superfluid vortex motion thermally activated against the pinning energy barriers. They interpret the observed post-glitch behavior as resulting from recoupling of the crust to the crustal neutron superfluid and obtained an excellent fit to the observational data (Alpar et al. 1984b and 1985).

The thermal property of the neutron star has been studied through the cooling of the neutron star. The thermal evolution of the neutron star is now a promising research field in order to know its internal structure since the recent experiment is making the measurement of its surface temperature possible. Detailed cooling calculations have been performed by several authors (Glen and Sutherland 1980; Van Riper and Lamb 1981; Nomoto and Tsuruta 1981; Richardson et al. 1981; see Tsuruta 1986 for a review) for various cases from the standard one to the exotic one invoking the pion-condensation or quark-matter in the central core. The calculated cooling curves have been compared with the observational results obtained by Einstein Observatory. The observational data available now, however, are not enough to select a distinct model on the internal structure among several possibilities.

It is important to note that the dynamical and thermal properties are not independent, but influence each other. In fact, most glitch models which invoke the differential rotation in the neutron star interior predict the internal heat generation due to the dynamical frictions among different components. Based on the mechanism of the frictional heating, Greenstein (1975) and Harding, Guyer and Greenstein (1978) calculated the temperature of the star as a function of time using the simple two component model. The results of these studies predict that the temperature becomes almost independent of time at large time and hence all the long period pulsars, or old neutron stars have essentially the same temperature.

In this paper we study the thermal and dynamicl evolution of the star. Especially, using the heat generation formula as given by the superfluid vortex creep theory (Alpar et al. 1984a), we examine the effect of the internal energy dissipation on the thermal evolution of the neutron star. In §II the basic equations to describe the thermal and rotational evolution of the neutron star are derived. In §III the cooling curves calculated with and without the internal heating are shown and compared. In §IV we set constraints on the internal properties of the neutron stars using the upper limits on the surface temperature of the nearby pulsars obtained by the Einstein observatory (Helfand, Chanan, and Novick 1980: Hefland 1983).

II. MODEL

a) *Physical Picture*

Neutron stars are expected to consist of four, or possibly five, distinct regions (see Alpar, Langer, and Sauls 1984; Lamb 1985): (1) a surface, which may be a solid or liquid, depending on the temperature and the strength of the surface magnetic field; (2) an outer crust, consisting of a solid lattice of nuclei embedded in a sea of relativistic degenerate electrons; (3) an inner crust, consisting of a solid lattice of nuclei embedded in a sea of superfluid neutrons and relativistic electrons; (4) a core, consisting mainly of superfluid neutrons but also including a dilute plasma of normal electrons and superconducting protons; and (5) possibly, in heavier stars, a distinct inner core, which might consist of condensed pions or other exotic states of matter.

Since the neutron star rotates, the neutron superfluid in the interior forms an array of vortex lines parallel to the rotation axis. The neutron vortices in the inner crust are expected to be pinned to the lattice nuclei present there, since the energy cost per particle to create the normal core of the vortex line is reduced by pinning (Anderson and Itoh 1975; Pines et al. 1980). Vortex lines thermally activated against the pinning energy barrier move outwards because of the outward force exerting on the vortex line (Alpar et al. 1984a). This outward force is the Magnus force caused by the difference in angular velocity between the pinned vortex line (and hence crustal nuclei) and the ambient neutron liquid. In this way the neutron superfluid in the inner crust couples to the crust through the vortex creep and shares the general spin-down of the neutron star caused by the external torque. It should be noted that the vortex creep motion accompanies the energy dissipation since the rotation of the superfluid in the inner crust is decelerated.

Recently, Alpar, Langer, and Sauls (1984) have shown that the neutron superfluid vortices in the core are strongly magnetized due to dragging of superfluid protons by the superfluid neutrons circulating around each neutron vortex. Consequently, the neutron superfluid in the core couples to the charged particles and to the crust in a time ~ 400 $\underline{P}$(s), where P is the rotation period of the star. Hence, in the time scale considered here, the core and the crust except for the neutron superfluid in the inner crust rotates together with the same speed

b) *Rotational Evolution*

The rotational motion of the crust is determined by the external torque N_{ext} acting on the star and the internal torque N_{int} caused by its coupling to the superfluid in the inner crust:

$$I_c\dot{\Omega}_c = N_{ext} + N_{int} \quad . \tag{1}$$

Here Ω_c is the angular velocity of the crust and I_c the moment of inertia of the crustal lattice plus all the other stellar material that tightly couples to it. Denoting the moment of inertia of the neutron superfluid in the pinning region by I_p and the angular velocity there by Ω_p, the internal torque may be written as

$$N_{int} = -\int \dot{\Omega}_p dI_p \sim -I_p\dot{\Omega}_p \quad . \tag{2}$$

The strong magnetic field of the neutron star is considered to be the most important cause of external braking. Here for the sake of illustration we assume that the braking torque is that due to magnetic dipole radiation:

$$N_{ext} = -\frac{2}{3}(\mu\sin\alpha)^2\left(\frac{\Omega_c}{c}\right)^3 \quad , \tag{3}$$

Here μ is the magnetic dipole moment, α is the angle between the rotation axis and the dipole field, and c is the velocity of light.

In dynamical equilibrium every part of the star decelerates at the same rate:

$$\dot{\Omega}_c = \dot{\Omega}_p \quad . \tag{4}$$

Using equations (2) - (4), and assuming the magnetic field constant with time, equation (1) is integrated to yield

$$\Omega_c = \frac{\sqrt{3}}{2} c^{3/2} \frac{I^{1/2}}{\mu \sin\alpha} \frac{1}{(t+\tau_0)^{1/2}} \quad , \tag{5}$$

where $I = I_p + I_c$, is the total moment of inertia and employing the initial condition $\Omega_c = \Omega_{ci}$ at t=0, the initial spin-down time τ_0 is defined by

$$\tau_0 = \frac{3}{4} \frac{I c^3}{(\mu \sin\alpha)^2} \frac{1}{\Omega_{ci}^2} \quad . \tag{6}$$

In a situation of our interest the internal temperature T is sufficiently low as compared with the pinning energy E_p, $kT << E_p \sim 1$ MeV, where k is theBoltzmann constant. Then, the equation of motion for the pinned superfluid (Alpar et al. 1984a) can be approximated by

$$\dot{\Omega}_p = -\frac{2\eta V_0}{r_p} \Omega_p \exp[-\frac{E_p}{kT}(1-\omega/\omega_{cr})] \quad . \tag{7}$$

Here ω is the angular velocity lag defined by

$$\omega \equiv \Omega_p - \Omega_c \quad . \tag{8}$$

V_0 is a typical velocity of microscopic vortex motion between the pinning centers with the value of ~ 10^7 cm/s. r_p denotes the radius of the pinning site which is almost equal to the radius of the star. η is a parameter of order of one which represents the differential rotation in the pinning region. ω_{cr} is the critical value of angular velocity lag ω at which the Magnus force exceeds the pinning force and the superfluid vortex unpins from the nuclei (Alpar et al. 1984a). The value of ω_{cr} depends strongly on the pinning condition in the inner crust. Depending on the microscopic parameters on the lattice nuclei and vortices, three characteristic pinning regimes can be considered: strong pinning (pinning force is strong enough to displace nuclei from their equilibrium sites in the lattice), weak pinning (vortex core pins only to those nuclei that coincide with the vortex line along its path without displacing nuclei or bending) and superweak pinning (coherence length of the vortex line core encompasses many nuclei within its diameter and moving the vortex line yields little difference in the available pinning energy). The calculation by Alpar et al. (1984b) shows that the critical angular velocity lag is in the same range ω_{cr} = 10-20, ω_{cr} = 0.1 and $\omega_{cr} < 0.1$ for strong, weak, and supewrweak pinnings, respectively.

The angular velocity lag in dynamical equilibrium is estimated from rewriting Eq. (7):

$$1 - \omega/\omega_{cr} = \frac{kT}{E_p} \ln\left(\frac{2\eta V_0}{r_p} \frac{\Omega_p}{|\dot{\Omega}_p|}\right) \quad . \tag{9}$$

In Eq. (9), E_p ~ 1 MeV, $kT \leq 30$ KeV and the logarithmic factor is in the range 25 - 40. Hence, it is seen that the equilibrium lag is almost equal to ω_{cr} and can be approximated as

$$\omega \sim \omega_{cr} \quad . \tag{10}$$

c) *Thermal Evolution*

The thermal evolution of the neutron star is described by

$$C_V \dot{T} = H - \Lambda_\nu - \Lambda_\gamma \quad , \tag{11}$$

where C_V is the heat capacity, H the heating rate, Λ_ν the neutrino cooling rate and Λ_γ the photon cooling rate. The heat capacity for the degenerate matter is expressed as

$$C_V = aT \quad , \tag{12}$$

where a is constant. In the hot early stage the neutron star cools by the neutrino emission (for a review, see Baym and Pethick 1979):

$$\Lambda_\nu = \lambda_\nu T^n \quad , \tag{13}$$

where λ_ν and n are constants. The dominant neutrino cooling processes at the late times of interest to us are neutrino pair bremsstrahlung process on the nuclei or the pion-induced β-decay process, depending on the interior model of the star. Both processes yield n = 6.

For the neutrino cooling rate, hereafter, we use this formula. When the neutron star cools down, the photon cooling becomes dominant:

$$\Lambda_\gamma = 4\pi R^2 \sigma T_s^4 = \lambda_\gamma T^m \quad , \tag{14}$$

where R is the radius of the star, σ is the Stefan-Botlzmann constant, T_s is the effective surface temperature, and λ_γ and m are constants. In order to relate the internal temperature to the surface temperature we employ the formula derived from the study of the envelope by Gudmundsson, Pethick and Epstein (1983):

$$T_s^4 = \frac{GM}{R^2} \left(1 - \frac{2GM}{c^2 R}\right)^{-1/2} \left(1.5 \times 10^{-8} T^{2.2}\right) \quad , \tag{15}$$

where M is the mass of the star, and G is the gravitational constant.

The role of internal energy dissipation due to vortex creep is estimated by

$$H = \int \omega |\dot{\Omega}_p| \, dI_p \equiv I_p \bar{\omega}_{cr} |\dot{\Omega}_p| \quad , \tag{16}$$

where Eq.(10) is used and ω_{cr} is an appropriate average of ω_{cr} through the pinning layer. On combining equation (16) with Eq. (5), the heating rate is expressed as a function of time:

$$H = \frac{\sqrt{3}}{4} \frac{c^{3/2}}{\mu \sin\alpha} \sqrt{I} \, I_p \bar{\omega}_{cr} (t + \tau_0)^{-3/2} \quad . \tag{17}$$

We note that equation (17) simplifies the calculation of the thermal history with frictional heating since it reduces the differential equations to be solved to only one (eq.[11]).

III. RESULTS

a) *Assumptions*

We have calculated the cooling curves of the neutron star both with and without the internal heating. Figures 1 and 2 illustrate the photon luminosity L_∞ and effective surface temperature T_∞ observed far from the star as a function of the time t_∞ measured also far from the star. In Fig. 1 the model neutron star constructed with the stiff equation of state (Pandharipande and Smith 1975; see also Pandharipande, Pines, and Smith 1976) is considered and the neutrino pair bremsstrahlung process is employed. In Fig. 2 the pion-condensation is assumed to exist in the central core of the neutron star constructed with the soft equation of state (Baym, Pethick, and Sutherland 1971). Figures 1 and 2 correspond to the "standard" and "exotic" cooling cases in the past works, respectively. The mass of the neutron star used is 1.4 $M_\odot$. The moment of inertia of the pinning region is set as I_p = 0.14 I for the stiff star and $I_p = 2.5\times10^{-3}$ I for the soft star (Nandkumar 1985). The initial spin-down time is taken as τ_0 = 300 y. The cooling curves shown in Figs. 1 and 2 do not depend on the initial condition in the time range of our interest ($t \geq 10^3$ y) unless the initial temperature set at $t = 10^2$ y is unreasonably low.

Depending on the dominant cooling mechanism, the thermal history is generally divided into the two characteristic eras, early neutrino era (flat part in the cooling curve) and late photon era (steep part). The critical temperature which distinguishes the two eras is estimated by Eqs. (13) and (14) as

$$T_c = \left(\frac{\lambda_\gamma}{\lambda_\nu}\right)^{1/(n-m)} . \qquad (18)$$

The effective surface temperature which corresponds to this critical temperature is T_∞ = 9.7×10^5 K in Fig.1 and $T_\infty = 1.0\times10^5$ K in Fig.2.

b) *Neutrino Cooling Era*

Figures 1 and 2 show that the internal heating has little influence on the surface photon luminosity in the neutrino era even when ω_{cr} is relatively large. In Figs. 1 and 2 the internal energy dissipation rate (H) exceeds the thermal inertia term ($-C_V\dot{T}$ term in Eq.(11)) at $\omega_{cr} > 0.1$ and at $\omega_{cr} > 0.01$, respectively. In spite of this large additional energy the enhancement of the surface photon luminosity from the no heating case is not so large. This result arises from the fact that the neutrino cooling rate is strongly dependent on the temperature ($\Lambda_\gamma \propto T^6$). When H >> $|C_V\dot{T}|$, the balance of the neutrino cooling rate with the internal heating rate determines the internal temperature, which has a very weak dependence on the internal heating rate ($T \propto H^{1/6}$). Therefore, the surface photon luminosity increases slowly with the increasing heating rate ($L_\infty \propto T^{2.2} \propto H^{1.1/3}$). It should be noted, however, that in the strong pinning regime the internal heating effect becomes appreciable and yields the surface photon luminosity more than a factor of 4 larger than that in the no heating case.

It is observed in Figs. 1 and 2 that the cooling curves at $t \geq 10^3$ y in the neutrino era have almost the same slope irrespective of the heating or no heating. This observation is justified by the analytical solution which gives a good fit to the numerical solution. Neglecting the photon cooling term and making use of Eqs. (12), (13) and (17), Eq. (11) can be solved as

$$T = \xi(t + \tau_0)^{-1/4} \quad , \tag{19}$$

where ξ is the solution of the polynomial equation given by

$$\lambda_v \xi^6 - \frac{a}{4}\xi^2 - \frac{\sqrt{3}}{4}\frac{c^{3/2}}{\mu \sin\alpha}\sqrt{I}\, I_p \bar{\omega}_{cr} = 0 \quad . \tag{20}$$

Equation (19) together with Eqs.(14) and (15) indicates the constant slope of 0.55 for the surface photon luminosity at times $t >> \tau_0$.

c) *Photon Cooling Era*

It should be emphasized that the inclusion of the internal heating completely changes the conventional picture of the cooling in the photon era as seen in Figs. 1 and 2. According to the previous works, the cooling curve in the photon era has a steep slope as illustrated by the dashed line in Figs. 1 and 2. Whereas, the solid lines show that the energy dissipation due to the vortex creep makes the cooling of the photon era much slower. Consequently, the cooling calculation with the internal heating predicts at least an order of magnitude larger surface photon luminosity than the one without it for the old neutron star with the age of $t_\infty > 10^6$ y.

In the photon cooling era the heat content of the star is negligible compared with the heat frictionally generated during the cooling time (~T/|T|) and hence the thermal evolution is determined by the heating and cooling terms. Balancing the heating rate due to the vortex creep with the photon cooling rate, we can derive an analytical solution which approximates the numerical results in Figs. 1 and 2 fairly well:

$$T = \left\{\frac{\sqrt{3}}{4}\frac{c^{3/2}}{\lambda_\gamma}\frac{\sqrt{I}}{\mu \sin\alpha} I_p \bar{\omega}_{cr}\right\}^{1/2.2} t^{-3/4.4} \quad . \tag{21}$$

It is worth pointing out that the analytical approximation which describes the cooling of the photon era in the no heating case is derived from Eq.(11) by neglecting H and Λ_v terms and then integrating:

$$T = \left\{ \frac{\lambda_\gamma}{5a} (t - t_c) + \frac{1}{T_c^{0.2}} \right\}^{-5} \quad , \tag{22}$$

where t_c is the time when the temperature given by Eq. (19) reaches the critical temperature T_c and the initial condition used at the integration is $T = T_c$ at $t = t_c$. Equations (21) and (22) indicate the temperatures of the old neutron star vary as $T \propto t^{-3/4.4}$ and $T \propto t^{-5}$ in cases with and without the internal heating, respectively. Hence, it is clearly known how the cooling of the old star is slowed down by the internal energy dissipation.

b) *Effect of Magnetic Field Decay*

In the above discussion we have assumed the magnetic field strength is constant with time. In connection with the wide scatter of points in P–P diagram of pulsars, however, the possibility of the magnetic field decay is also suggested (see, for example Manchester and Taylor 1977). Recently, Lyne, Manchester and Taylor (1985) have conducted a statistical analysis using a sample of 316 pulsars and shown that the observed distribution and evolution of pulsars is remarkably well described by the Gunn and Ostriker model (1970) in which the exponential decay of magnetic field is assumed. They obtained the value of ~ 9×10^6 y for the time constant of the magnetic field decay. Recently, Taam and van der Heuvel (1986) have also pointed out that the presently available data on magnetic field strengths of neutron stars in binary systems are consistent with the assumption of the exponential field decay on a time scale of ~5×10^6 y.

In order to see the effect of the magnetic field decay on the cooling curve, let us consider the case of the exponential decay of the magnetic field:

$$\mu = \mu_0 e^{-t/t_d} \quad , \tag{23}$$

where μ_0 is the initial magnetic dipole moment and t_d the decay time constant. If $t_d \geq 10^6$ y as often suggested, the effect of the magnetic field decay may appear in the photon cooling era as seen from Figs. 1 and 2. In order to estimate the maximum effect here we neglect the Ohmic heating due to the magnetic field decay. Introducing the field decay given by Eq. (23), the analytical solution of Eq. (21) for the photon cooling era is replaced by

$$T = \left\{\frac{\sqrt{3}}{4}\frac{c^{3/2}}{\lambda_\gamma}\frac{\sqrt{I}}{\mu_0 \sin\alpha} I_p\, \bar{\omega}_{cr}\right\}^{1/2.2} \frac{e^{-t/1.1t_d}}{\{(1-e^{-2t/t_d})t_d/2\}^{3/4.4}} \quad . \tag{24}$$

It is noted that Eq. (24) converges to Eq. (21) in the limit of $t_d \rightarrow \infty$.

Equation (24) shows that when the magnetic field decays, the neutron star cools exponentially at $t > t_d$ with the time constant of ~ 1.1 t_d even though the internal heating is included. This is because the magnetic field decay lowers the decceleration rate of neutron star rotation and hence the heat dissipation rate. After the magnetic field decayed away ($t >> t_d$), the neutron star will cool steeply following Eq. (22).

At $t < t_d$, however, the difference between Eqs. (21) and (24) is insignificant and both formula give almost the same temperature. If we adopt $t_d \sim 10^7$ y as suggested by Lyne, Manchester, and Taylor (1985), the cooling curve with the inernal heating predicts considerably larger surface photon luminosity at the time of 10^6-10^7 y than that with no heating. Even if the magnetic field decay time is as small as 10^6 y, there is a substantial difference in surface photon luminosity around the time of t ~ 10^6 y between the cases with and without the internal heating. Hence, it is quite likely that the internal heating will slow down the cooling of the neutron star appreciably at least at the beginning part of the photon cooling era.

IV. DISCUSSION AND CONCLUDING REMARKS

(a) Constraints on the internal parameters

The Einstein Observatory looked at the nearby pulsars with the spin down age more than 10^6 y and set upper limits on their surface thermal radiations (Helfand, Chanan, and Novick 1980; Helfand 1983). The upper limit on the surface temperature is in the range of 2×10^5 K to 9×10^5 K. As seen from the cooling curves in Figs.1 and 2, these upper limits are still too high to know about the way of cooling, "standard" or "exotic".

The upper limits for a few pulsars, however, can be used to set some constraints on the internal parameters of the neutron star if we assume no exotic matter in its central core. According to our study in the previous sections, it is likely that in the "standard" cooling case the neutron star older than 10^6 y is in the photon cooling era and cooling maintaining the thermal balance between the photon cooling and internal heating rates. Neglecting the general relativistic effect, the thermal balance is written as

$$L_\infty = I_p \,\bar{\omega}_{cr}\, |\dot{\Omega}_c| \quad . \tag{25}$$

Using Eq.(25), the upper limits on the surface photon luminosity are translated into the upper limits on $I_p\, \omega_{cr}$ (g cm^2 rad s^{-1}), which is 2×10^{43} for PSR 1929 + 10, $(2\text{-}4)\times10^{44}$ for PSR 1642-03 and $(2\text{-}5)\times10^{44}$ for PSR 1706-16. The moment of inertia of the pinning region is expected to be

$I_p \sim I/10 \sim 10^{44}$ g cm^2 for the stiff star and $I_p \sim I/100 \sim 10^{43}$ g cm^2 for the moderately stiff star (Nandkumar 1985). The case of the stiff star with the strong pinning region gives $I_p\omega_{cr} \sim 10^{45}$ g cm^2 rad s^{-1}, which exceeds the upper limits for above pulsars. This fact indicates that the strong pinning regime in the stiff star which has the largest internal heating effect is less probable. The fitting of the vortex creep theory to the glitch observations (Alpar et al. 1984b and 1985) suggests $I_p/I \sim 10^{-2}$, which prefers the moderately stiff star. If we assume $I_p \sim 10^{43}$ g cm^2, the upper limit on $I_p\omega_{cr}$ for PSR 1929+10 implies the weak and/or superweak pinning regime (Alpar et al. 1984b). This indication is consistent with the resent suggetion by Chen et al. (1985) that the microscopic investigation of $^1S_0$ neutron pairing favors the weaking pinning condition over the strong pinning.

Eq.(25) is often used to estimate the surface thermal radiations from the long-period (old) pulsars (Alpar et al. 1984b and 1985). It should be mentioned, however, that in the "exotic" cooling case Eq.(25) is not yet applicable even at the time of 10^6–10^7 y. This is because the neutrino cooling rate is still dominant over the photon cooling rate even at this old age, especially in the strong pinnning case and hence the dissipated energy is emitted predominantly by the neutrinos as seen in Fig.2.

(b) Concluding remarks

We have shown that the internal heating plays an important role on the thermal evolution of the neutron star. The heat generation by the vortex creep motion predicts that the old neutron star with the age more than 10^6 y should still emit the considerable surface thermal radiations with the temperature of order of 10^5 K. If the nearby pulsars are selected, this thermal flux may be observable by future experiments, especially by the Space Telescope. Our preliminary search in the pulsar catalogue shows that there are at least half a dozen candidate sources which the expected flux is in the detection limit of the Space Telescope in the far UV band. It is quite expected that the detection or stringent limit will provide the important informations on the internal structure of the neutron star.

Finally, it should be mentioned that our results here are not limited to the vortex creep case, but also applicable to the case of the other heating mechanism as long as its heating rate is just proportional to the angular deceleration rate

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FIGURE CAPTIONS

Fig. 1 Cooling curves of the stiff neutron star in the "standard" case. The photon luminosity L_∞ and effective surface temperature T_∞ observed far from the star are illustrated as a function of time t_∞ measured far from the star. The solid and dashed lines depict the thermal histories with and without the internal heating due to the vortex creep, respectively. The number on the curve represents the critical angular velocity lag ω_{cr} (rad/s) needed for the unpinning of the superfluid vortex from the lattice nuclei. The physical parameters and formulae used are: mass, $M = 1.4\ M_O$; radius, $R = 15.8$ km; total moment of inertia, $I = 2.18 \times 10^{45}$ g cm^2; moment of inertia of the pinning layer, $I_p = 0.14\ I = 3.05\times10^{44}$ g cm^2; heat capacity, $C_V = 2\times10^{29}$ T erg/K; cooling rate by neutrino pair bremsstrahlung, $\Lambda_\nu = 1.2\times10^{-16}\ T^6$ erg/s; photon cooling rate, $\Lambda_\gamma = 2.2\times10^{15}\ T^{2.2}$ erg/s; magnetic dipole moment, $\mu\sin\alpha = 5\times10^{30}$ gauss cm^3; initial spin-down time, $\tau_0 = 300$ y.

Fig. 2 Cooling curves of the soft neutron star in the "exotic" case with the pion-condensation central core. The details are the same as in Fig. 1. The physical parameters and formulae used are: mass, $M = 1.4\ M_O$ radius, $R = 7.36$ km; total moment of inertia, $I = 6.51\times10^{44}$ g cm^2; moment of inertia of the pinning layer, $I_p = 2.53\times10^{-3}\ I = 1.65\times10^{42}$ g cm^2; heat capacity, $C_V = 2.9\times10^{29}$ T erg/K, neutrino cooling rate by pion-condensation, $\Lambda_\nu = 3\times10^{-9}\ T^6$ erg/s; photon cooling rate, $\Lambda_\gamma = 2.9\times10^{15}\ T^{2.2}$ erg/s; magnetic dipole moment, $\mu\sin\alpha = 3\times10^{30}$ gauss cm^3; initial spin-down time, $\tau_0 = 300$ y.